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NRL Memorandum Report 2298

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Studies of Optical Augmentation With Picosecond Pulses

[Unclassified Title]

ROBERT C. ECKARDT AND HERBERT RABIN

Quantum Optics Branch
Optical Sciences Division

July 1971

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Picosecond Pulses for Resolution of Optical Elements by Retroreflection

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ABSTRACT

([redacted]) Picosecond optical pulses generated by a neodymium-glass mode-locked laser were employed in laboratory measurements of the retro-reflection from optical surfaces. These measurements were directed at a determination of the minimum separation distance between surfaces which could be resolved using either a photodiode or an image converter camera for detection. A minimum resolvable distance of 7.5 cm was obtained with a photodiode, and the camera yielded a value of 1.5 cm. In addition calculations have been made of the range at which the retroreflection technique may be employed for analyzing optical elements using short pulses. Ranges of several kilometers appear feasible.

PROBLEM STATUS

This is an interim report on one phase of a problem. Work on other phases continues.

AUTHORIZATION

NRL Problems N01-12 and N01-14.
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Robert C. Eckardt and Herbert Rabin
Quantum Optics Branch
Optical Sciences Division

I. INTRODUCTION

([redacted]) There has been a considerable interest in the use of radiation from lasers for purposes of obtaining a return signal from an object at a distance and thus obtaining information pertaining to the object. This indeed is the basis for optical radar when an object either scatters or diffusely reflects some of the incident radiation to a detector near the source. In the event that the object being probed itself is an optical device, in particular a device which is trained on or near the laser source, then there is the possibility of a strong and well directed reflection back in the direction of the source and this is commonly referred to as a "retroreflection." An example of this is provided by a corner cube reflector placed on the moon's surface in the lunar ranging experiment. In the applications of military interest, retroreflection is of interest as a possible means of knowing that you are being looked at, of identification of the particular optical device, and accordingly of anticipating a potential threat. The optical devices may include binoculars, periscopes, telescopes and other passive equipment, and also they include laser devices and other active systems. The human eye itself is, of course, a retroreflecting optical system.

([redacted]) In principle, it is possible to classify an optical device from which a retroreflection has been obtained if there is a return from the various constituent optical elements comprising the device. (More exactly every optical interface has a Fresnel reflection, so that a simple lens would have a reflection from both its front and back surfaces.) Classification is possible by noting a characteristic optical signature associated with the retroreflection. The spacing of the pulses in time gives information of the separation of optical surfaces in the unknown device, and the relative magnitudes of these time separated retroreflections bears a direct correspondence to the reflectivity of the surfaces. Since each optical device of a particular

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design has a unique combination of reflecting surfaces, in principle, the retroreturn from such a device provides a fingerprint which may be identified from a master library of such fingerprints.

([redacted]) It is clear that a map of the component elements of an optical device can only be obtained if there is sufficient resolution to separate individual reflections from the various optical surfaces. Since light travels at the enormous speed $c = 3\times10^{10}$ cm/sec, only ultrashort optical pulses would have sufficient resolving capability for the purposes here described. The typical Q-switched laser source provides pulses with half-widths of 10 to 20 nanoseconds (1 nsec = 10^{-9} sec). Since the spatial extent of a pulse is given by the produce $c\times\tau$, where τ is the pulse duration, Q-switched laser pulses will be in the range 300 to 600 cm in length. They clearly will be unable to resolve optical surfaces separated by tens of centimeters down to fractions of a centimeter. It is accordingly of interest to consider the use of picosecond optical pulses (1 psec = 10^{-12} sec) for retroreflection purposes. Such a pulse has an ultimate resolution in the neighborhood of .03 cm if its full potential is exercised. To take maximum advantage of such a short pulse a number of factors must be considered, perhaps the primary of which is the detector system used to record the retroreturns.

([redacted] This report considers some of the problems associated with the use of ultrashort pulses for interrogation of optical devices employing the retroreflection concept. In order to carry out the experimental portion of this work, a mode-locked neodymium-glass laser was employed which generates pulses less than 1 psec duration. This source, designed for other studies, was used because of its availability for this work and does not necessarily represent the most practical source for retroreflection probing. The full potential resolution of the pulses from this laser was not used, since conventional detection schemes were employed with rise times as long as 400 psec. As a preliminary study, it provided an initial look at what one could possibly expect to achieve with existing hardware. By defining the limits of resolution and operating conditions of an ultrashort retroreflection system in the laboratory under controlled conditions, the basis is set for more extensive study under more realistic conditions.

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II. EXPERIMENTAL MEASUREMENTS

([redacted]) Optical augmentation measurements were performed in the laboratory using an ultrashort pulse, mode-locked laser source and commercially available fast detection systems to monitor reflections from simple optical systems. The output of the mode-locked neodymium-glass laser source consisted of individual pulses of 3/4 picosecond duration evenly spaced by 9 nanoseconds in a mode-locked pulse train typically 500 nanoseconds long. The laser wavelength is 1.06 microns and peak powers reach 10^9 watts. The simple optical systems examined consisted of flat and parallel beamsplitters and also a simple telescope. Two types of detection systems were employed. These were a photodiode-oscilloscope system and an image converter camera. It was possible to detect a double reflection from two surfaces separated by $7\frac{1}{2}$ cm when using the photodiode. With the image converter camera it was possible to reduce the spacing to $1\frac{1}{2}$ cm while temporally resolving the double reflection.

(U) A brief description of the mode-locked laser is given here. This information exists in the open literature, and the article by DeMaria gives a thorough review (1). The longitudinal cavity modes of a laser can be coupled together by nonlinear interactions such as the saturable absorption produced in certain dye molecules. Mode-locking occurs when the phases of the different cavity modes are related in such a way that they interfere to synthesize a single short pulse within the resonant cavity of the laser. A portion of this pulse is emitted with each cavity round trip transit. The resultant laser output is a train of ultrashort pulses, evenly spaced by a few nanoseconds. The spectral bandwidth of the fluorescent lasing line determines the lower limit for pulse duration. With the broad spectral width of the neodymium-glass system this lower limit is approximately 0.2 picoseconds. The pulse duration of the laser used here was measured at NRL to be less than 0.73 picoseconds (2). This corresponds to a spatial extent of 0.022 cm. This feature indicates the high potential of the mode-locked neodymium-glass laser as a probe source in optical augmentation.

([redacted]) A diagram of the laser and a typical laboratory setup is shown in Fig. 1. The laser resonant cavity was formed by two flat parallel mirrors with reflectivities of 99% and 65%. The neodymium-glass laser rod was 6 inches long X 3/8 inch diameter with the ends diagonally cut at the Brewster angle. A dye cell containing the saturable absorption dye was placed inside the cavity near the 65% mirror. The ultrashort pulse train was directed into the optical system under test. In this case two flat parallel beamsplitters are shown. The reflections from the elements in the optical system were returned at a slight angle to the incident beam. The reflections were then directed to the photodetector by a right angle prism.

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(U) Both a photodiode and an image converter camera were used for detection of the reflected signal. The biplanar photodiode had an S-1 photocathode with approximately 0.04% quantum efficiency at 1.06 microns. The signal from the photodiode was displayed on a Tektronix type 519 travelling wave oscilloscope. Both photodiode and oscilloscope had rise times of slightly less than 0.3 nanosecond and a combined rise time of 0.4 nanosecond.

([redacted]) Oscilloscope recordings of the photodiode signal are shown in Figs. 2a-2e. The ultrashort pulse train observed in a single reflection is shown in Fig. 2a. The repetition with a period of 9 nanoseconds is due to the 9 nanosecond round-trip transit time of the laser resonant cavity and is characteristic of the laser output. The apparent pulse width displayed on the oscilloscope is nearly 1 nanosecond. As mentioned earlier, the optical pulse has a true width less than 1 picosecond, but appears broadened due to the longer rise time of the detector system. When a second beamsplitter was placed 30 cm from the first, two reflections of each ultrashort pulse were observed (Fig. 2b). Since light travels at a velocity of 3×10^{10} cm/sec or 30 cm/nanosecond, the 30 cm spacing between plates will cause the second reflection to traverse a path 60 cm longer than the first reflection and be delayed 2 nanoseconds from the first. The 2 nanosecond spacing is observed on the oscillogram. A third reflector was added as shown in Fig. 2c-2e with respective spacings of $12\frac{1}{2}$ cm, 10 cm, and $7\frac{1}{2}$ cm. The third reflection was well resolved for the $12\frac{1}{2}$ cm spacing, but it was just discernible for $7\frac{1}{2}$ cm separation.

([redacted]) In order to more closely simulate a practical situation, a test was made using an elbow telescope in place of the simple arrangement of beamsplitters. This device consists of an objective lens separated from a group of optical elements near the eye piece by a distance of about 25 cm (approximately the focal length of the objective lens.) These results are shown in Fig. 3. With the telescope at a distance of 2 meters or more from the detector only one reflection was seen in the oscillogram of the photodiode signal. This is attributed to retroreflections of several optical elements near the focus of the objective lens. With the telescope moved to within 20 cm of the detector two reflected pulses were displayed on the oscillogram. The first weak reflected pulse can be attributed to the objective lens. The second and more intense reflection corresponds to the reflection found previously for long distances. All of these surfaces were spaced within the $7\frac{1}{2}$ cm resolution distance associated with this detector. The reflections from the surfaces near the focal plane will be recollimated by the objective lens. Reflections from the objective lens will be more diverging and therefore less sensitive to direction. However, the intensity associated with the objective lens will decrease faster with distance from source. Consequently, only one retroreflection is observed at large distances due to the limited dynamic range of the

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detector. The signal itself is very large and in fact has been purposely attenuated by several orders of magnitude in order to avoid detector overloading.

(U) The image converter camera had slightly better temporal resolution than the photodiode-oscilloscope combination. Our measurements determined that this camera could resolve two pulses separated in time by 0.1 nanosecond. This pulse separation corresponds to a minimum resolvable distance separation of about 1.5 cm. This has been experimentally verified. A diagram of the image converter camera is shown in Fig. 4. An objective lens focuses an image on a photocathode. The electrons emitted from the photocathode are accelerated and then focused on a phosphor screen. The image on the phosphor screen is focused on photographic film by the relay lens. It is possible to shutter and deflect the electron beam with much greater speed than could be obtained with mechanical devices operating on an optical beam. The high temporal resolution is obtained by sweeping the image of a slit. The image converter tube is gated on at an appropriate time and a ramp voltage signal is applied to the deflection plates. The image of the slit is then swept from top to bottom across the phosphor screen. When the slit is illuminated an image is recorded on the photographic film. Temporal variations in slit illumination can be obtained from a densitometer trace of the photographic exposure.

([redacted]) The results using the image converter camera are shown in Fig. 5a-5d. This represents 20 nanoseconds along the horizontal axis, which is enough to contain the reflections associated with three pulses in the train. The reflections from two beamsplitters having various separations illuminated the slit of the camera. As can be seen from these results, pulses associated with a 1.5 cm separation of two reflectors are barely resolved (see arrows).

(U) At this pulse separation the camera is limited by space charge effects in the image converter tube. More intensity on the photocathode only caused blurring of the electron image. With less intensity at the photocathode the image on the phosphor screen was not bright enough to give a photographic exposure, even while using a *f*/1.2 relay lens and ASA 10,000 photographic film.

([redacted]) The two detector systems that were used are representative of what is available commercially, but their rise time is well above the state-of-the-art. An image converter camera with 10 picosecond resolution has been reported in Russian literature (3), and laboratories in Western countries are also working on converter tubes which will have picosecond resolution (4). What has to be done is first overcome space charge limitations with higher accelerating voltage and multiple stage image converter tubes. After space charge limitations are overcome, it is necessary to correct for the initial distribution of velocity of the

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photoelectrons. In principle, it should be possible to make other photodetectors as fast as the image converter camera. The major problem here is detection electronics. The fastest real-time oscilloscopes now have rise times of 0.3 nanosecond while sampling oscilloscopes are 10 times faster. With some adaptation it would be possible to utilize the repetitive characteristics of ultrashort pulse trains with the faster sampling electronics. With either of these approaches there is no reason why these measurements could not be extended to measuring the distance between the front and back surface of a single lens. However, the greatest difficulties do not appear to be temporal resolution. Large dynamic range in reflection from the same target, target orientation, and countermeasures taken at the target will present more difficult problems. These problems would be encountered in any of the various systems proposed for optical augmentation.

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III. CALCULATIONS AND DISCUSSION OF RESULTS

(U) The typical mode-locked neodymium-glass laser output consists of a train of ultrashort pulses separated by the round-trip transit time. Energy of the individual ultrashort pulses ranges from 1 to 10 millijoules. The energy of a single photon of 1.06μ wavelength is 1.87×10^{-19} joules. Consequently, a one millijoule pulse at this wavelength will contain 5.3×10^{15} photons. This is typical of the unattenuated pulses used in experimental work reported in the previous section. However, the state-of-the-art is sufficiently advanced to produce pulses of much higher total energies. With present technology it is possible to switch a single short pulse out of the pulse train and amplify it to 1 to 100 joules. A 10 joule pulse will consist of 5.3×10^{19} photons. With the present detector technology approximately 3×10^{5} photons would be required to obtain a 10:1 signal-to-noise ratio under ideal conditions (see appendix). It should be possible to detect such signals with only 10^{-14} of the energy of the laser probe signal; for the one millijoule pulse 10^{-10} of the energy of the probe signal is required. The problem of detectors will be considered in more detail later. First, reflection from simple optical surfaces will be discussed.

(U) Three simple surfaces are considered: (1) a diffuse reflector; (2) a specularly reflecting spherical surface; and (3) a specularly reflecting flat mirror. The results of this analysis are contained in Table 1. In these three cases it is assumed that the surface is illuminated normally by a probe beam with intensity I_o. For the diffuse reflector a disc of radius a and diffuse reflectivity R is used. The point at which a reflection is observed is given by the spherical coordinates r and θ. The distance from the observation point to the surface is r, and θ is the angle between direction of observation and surface normal. With these definitions the intensity $I(r,\theta)$ of diffusely reflected light observed at the point (r,θ) is given by

$$I(r,\theta) = \frac{a^2 R I_o}{r^2} \cos\theta \qquad \theta \leq \frac{\pi}{2}$$

$$= 0 \,. \qquad \theta \geq \frac{\pi}{2} \tag{1}$$

(U) The specular reflection from a convex spherical surface of radius of curvature ρ diverges from a virtual focus distance $\frac{1}{2}\rho$ behind the surface. For a surface of diameter 2a and reflectivity R, the reflected intensity at a distance r from the surface is given by

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$$I(r,\theta) = I_o R\left(\frac{\frac{1}{2}\rho}{r+\frac{1}{2}\rho}\right)^2 \qquad \theta < \sin^{-1}(\tfrac{1}{2}a/\rho)$$

$$= 0 \; . \qquad \theta > \sin^{-1}(\tfrac{1}{2}a/\rho) \tag{2}$$

As indicated by the θ dependence, the reflected signal is uniformly distributed in a cone of angular diameter $2 \sin^{-1}(\frac{1}{2}a/\rho)$. This result is valid except near $\theta = \sin^{-1}(\frac{1}{2}a/\rho)$ where it is necessary to consider the effects of diffraction.

(U) The only case where it is not necessary to consider diffraction in reflection from a flat surface is for distances $r \ll a^2/\lambda$. Here λ is the wavelength of light and a is the radius of the reflector. At these short distances reflected intensity is I_0R in the geometrical beam and zero outside the beam. At longer distances it is necessary to solve a diffraction integral. At large distances the diffraction integral can be solved to give the angular distribution of the reflected beam (5):

$$I(r,\theta) = \frac{k^2a^2RI_o}{r^2}\left[\frac{J_1(ka\sin\theta)}{ka\sin\theta}\right]^2 \; . \tag{3}$$

This is the familiar Fraunhofer diffraction pattern of a circular aperture. Here $k = 2\pi/\lambda$; a = radius of circular aperture; R = specular reflectivity; and J_1 is a first order Bessel function. At intermediate distances it is necessary to consider numerical solutions of the diffraction integral or evaluate solutions in the form of series of Bessel functions. This will not be done here. For the typical dimension $a = 2.5$ cm, and $\lambda = 1.06\mu$, the intermediate region is that for which $r \approx a^2/\lambda = 590$ meters.

([redacted]) The case of the flat specular reflector most nearly approximates retroreflection in a well corrected optical system. Reflection from a spherical surface would apply to the surfaces of the objective lens and intermediate reflecting surfaces. Diffuse reflection would apply to reflections from other than optical surfaces in the neighborhood of the target. The results are summarized for a set of typical values in Table 1.

[redacted]

(U) Table 1

Relative Reflected Intensities $\frac{I}{I_o}$ from Simple Surfaces

Distance	Relative Intensity Return by a 5.0 cm Diameter Reflector		
(Meters)	Diffuse Reflector[a] disc radius a = 2.5 cm	Spherical Surface[b] radius of curvature ρ = 25 cm	Flat Surface[b] disc radius a = 2.5 cm
r= 1 m	6.25×10^{-4}	1.23×10^{-2}	1
10 m	6.25×10^{-6}	1.52×10^{-4}	1
100 m	6.25×10^{-8}	1.56×10^{-6}	--[c]
1 km	6.25×10^{-10}	1.56×10^{-8}	--[c]
10 km	6.25×10^{-12}	1.56×10^{-10}	3.4×10^{-2}
100 km	6.25×10^{-14}	1.56×10^{-12}	3.4×10^{-4}

[a] Assuming incident energy is completely reradiated uniformly in space, i.e. R = 1.

[b] Assuming perfect specular reflectance, i.e. R = 1.

[c] Not calculated due to complexity for these intermediate distances.

([redacted]) The calculations for simple reflecting surfaces show how large variations occur in reflected signals. If it is required to simultaneously deal with retroreflections and reflections from various spherical and flat surfaces within an optical system, detectors will have to have very large dynamic ranges. As an example consider the simple telescope described below.

([redacted]) The telescope considered here is of the simplest type. It has only 3 optical elements: (1) a single element plano-convex objective lens, (2) a reticle at the objective focus, and (3) a single element plano-convex eye lens. The diameter of the objective lens is 5 cm, the focal length is 50 cm, and the thickness is 5 mm. The eye lens has a 5 cm focal length and 2 mm thickness. The thickness of the reticle is 1.5 mm. The index of refraction can be assumed to be 1.5 for all three optical elements. With this index there is 4% reflection and 96% transmission at each surface. This simple telescope is not representative of the highly corrected, sophisticated optical systems which would be encountered in practice. However, in analyzing this system we will

[redacted]

obtain insight into the problems of more sophisticated systems. In the analysis first order geometrical optics with thin lens approximations is used. The results are summarized below.

([redacted]) We assume a collimated probe of uniform intensity parallel to the optical centerline of the telescope. Six reflections from the six air-glass interfaces are considered. The characteristics of the reflected radiation are given in Table 2A. The relative energy collected by a 5 cm aperture is calculated in Table 2B. The following surface reflections have been considered:

1. Reflection from first surface of objective.
2. Reflection from second surface of objective.
3. Reflection from first surface of reticle.
4. Reflection from second surface of reticle.
5. Reflection from first surface of eye lens.
6. Reflection from second surface of eye lens.

([redacted]) Table 2A

Reflections from Simple Telescope

Reflection[a]	Delay (Sec)	Focus of reflected beam (cm)	Angular extent	Percentage of incident beam in reflected beam
1	0	12.5[b]	$22^{\circ}37'$	4
2	$.5 \times 10^{-10}$	25[c]	$11^{\circ}25'$	3.69
3	33.18×10^{-10}	12500[b]	$0^{\circ}\ 1'23''$	3.40
4	33.33×10^{-10}	∞ (retro)	5" (diffraction)	3.13
5	36.67×10^{-10}	300[c]	$0^{\circ}57'$	2.00
6	36.87×10^{-10}	675[c]	$0^{\circ}26'$	0.13

[a]See text for description.

[b]Virtual focus behind objective.

[c]Real focus in front of objective.

[redacted]

([redacted]) Table 2B

Relative Return Signal Collected by a 5 cm Aperture[a]

Reflection	Distance						
	0	1m	10m	100m	1km	10km	100km
1	4.00×10^{-2}	4.92×10^{-4}	6.20×10^{-6}	6.24×10^{-8}	6.24×10^{-10}	6.24×10^{-12}	6.24×10^{-14}
2	3.69×10^{-2}	4.10×10^{-3}	2.42×10^{-5}	2.32×10^{-7}	2.31×10^{-9}	2.31×10^{-11}	2.31×10^{-13}
3	3.40×10^{-2}	3.35×10^{-2}	2.91×10^{-2}	1.05×10^{-2}	4.18×10^{-4}	5.31×10^{-6}	5.27×10^{-8}
4	3.13×10^{-2}	3.13×10^{-2}	3.13×10^{-2}	3.12×10^{-2}	2.48×10^{-2}	1.04×10^{-3}	1.07×10^{-5}
5	2.00×10^{-2}	2.00×10^{-2}	3.67×10^{-3}	1.92×10^{-5}	1.81×10^{-7}	1.81×10^{-9}	1.81×10^{-11}
6	1.30×10^{-3}	1.39×10^{-3}	1.30×10^{-3}	6.83×10^{-6}	6.01×10^{-8}	5.96×10^{-10}	5.93×10^{-12}

[a] The portion of the light incident on the simple telescope collected by a 5 cm aperture at various distances.

[redacted]

([redacted]) The numerical results in Table 2B indicate the problem in large variations in reflected amplitude. When all the light reflected is collected (i.e. distance = 0), the relative signal amplitude varies from 4.0×10^{-2} to 1.3×10^{-3} or 31:1. At ten meters the ratio is 5000:1, and it increases to 1.9×10^{8}:1 in the far field! Considerable progress in detector technology is required to accommodate this range of 10^{8} in signal amplitude while maintaining fast detector response. This accounts for the experimental results in the previous section where only one signal was detected at the 2 meter source-telescope distance with the elbow telescope in the laboratory measurements whereas 2 pulses were detected for 20 cm source-telescope distances. In going from 20 cm to 2 meters the observed reflections from the objective lens would decrease two orders of magnitude while the retroreflection (primarily from the reticle) would be unchanged. Further considerations are given in the Appendix relating to detectors.

([redacted]) These calculations do indicate that it is possible to detect individual reflections from separate surfaces in optical systems at a great distance. It was stated in the first part of this section that only 10^{-14} of the energy of an amplified ultrashort pulse is required for detection by a theoretically limited photoelectric detector. In the example of the simple three element telescope it was found that more than 10^{-14} of the energy incident on the telescope was returned in each of six single surface reflections when the telescope was at a distance of 100 km. Of course, these calculations are for an ideal situation. Difficult problems such as pointing the probe, atmospheric transmission, damage of the optical device, and separating the return signal from spurious background have not been considered in the calculation.

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IV. CONCLUSIONS

([redacted]) The results obtained here indicated that an optical radar system based upon retroreflection is possible. A resolution of several centimeters between optical elements can be obtained with the aid of a commercially available photodiode. This resolution is substantially better than that available in existing Q-switched laser rangefinder systems. Calculations indicate that a range of several kilometers is possible for typical systems which might be interrogated. For any practical system operating at a sufficiently long range, atmospheric distortion and spreading on the beam would have to be considered. These effects were not evaluated in this preliminary investigation.

([redacted]) The retroreflection detector is central to development of a suitable system. First of all, it was shown that the 400 psec rise time of the photodiode-oscilloscope detection system used in the present work limited the resolution between optical elements to 7.5 cm. This resolution can be reduced to approximately 1.5 cm using an image converter camera, however, this system is more complex and is much more inconvenient that the simple oscilloscope display with a photodiode. Nevertheless, the image converter camera provides an attractive possibility in that the time resolution has been reduced to less than 10 picoseconds in some models. The full benefit of still shorter pulse widths of the laser could only be fully realized using a fairly complex autocorrelation method developed at NRL (2) or other complicated methods developed elsewhere. Another detector problem is that of dynamic range. A large dynamic range is highly desirable and this is not now available. A possible approach to the problem is the use of a number of detectors, each functioning over a specific range. An additional problem is a lack of knowledge of target factors such as reflectivity, off-axis behavior, and ratio of retro to ordinary optical radar signal in practical situations. At this point it is not clear as to the detectability of an optical device which is not directly looking at the probe system, particularly when there is a noisy background due to extraneous reflections.

([redacted]) In spite of these problems, it is believed that picosecond laser retroreflection radar has sufficient promise to warrant a continuing interest and effort. In the past few years, great progress has been made both in this and other laboratories in understanding the dynamics and operating characteristics of picosecond lasers. As a result, a considerable improvement in the reliability and stability of these systems has been achieved and further improvement is contemplated in both reliability and output power. A similar history in the use of other types of laser systems has been experienced. It is quite possible that other picosecond laser systems and detectors will be developed. As an example, picosecond structure in injection lasers has been reported recently (6).

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ACKNOWLEDGEMENT

It is a pleasure to acknowledge the contributions of Dr. Marvin Hass and Mr. James Tucker in reading the manuscript and making useful comments.

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V. APPENDIX

Detector Considerations

([redacted]) In the analysis of the telescope many of the limitations of photoelectric detectors were ignored. The fastest photodetectors now available have rise times of 0.1 nsec which would allow resolution of 1.5 cm. This would not be sufficient to resolve reflections from the front and back surfaces of an optical element. Instead the sum of the two reflections would be detected and displayed as a single pulse.

(U) Photocathodes with S-1 spectral response are best suited for detection of 1.06μ radiation from the neodymium-glass laser. At this wavelength the quantum efficiency of the S-1 surface is 0.00038; in other words on the average 1 photoelectron is generated for every 2600 photons incident on the photocathode. Approximately 100 photoelectrons are required to resolve pulse height with 10% accuracy; this in turn would require 2.6×10^5 photons at 1.06μ. Other wavelengths of interest are 6943Å (ruby laser) and 5300Å (second harmonic of neodymium.) The S-20 photocathode has quantum efficiency of .023 at 6943Å and 0.11 at 5300Å.

(U) It is also necessary to consider the limitations of display electronics. Oscilloscope rise times of 0.3 nsec are available, but sensitivity is limited to 10 volts/cm. If rise time is relaxed to 1.5 nsec it is possible to have sensitivity of 0.01 volts per cm. With 1.5 nsec rise time, resolution would be reduced to less than 45 cm separation of optical elements. Consider now what can be done with photodiodes and photomultipliers which are available. To produce a 1 volt pulse across the 125 ohm termination in the .3 nsec rise time oscilloscope requires 8 ma $\times$ 0.6 nsec = 4.8×10^{-12} coulomb or 3×10^7 photoelectrons. Considering the 0.00038 quantum efficiency this requirement is 7.8×10^{10} photons. Recall there are 5.3×10^{15} photons in a 1 millijoule pulse. This would limit the reflection returns which could be detected in our experimental setup to 10^{-5} and larger. Photomultipliers which have adequate current capabilities to produce a 10 volt signal across 125 ohms are available. Typical current amplification is 10^6, and rise time of 0.8 nsec possible. Using such a photomultiplier in our experimental setup would make it possible to detect reflections as small as 10^{-11} of the incident energy. Thus ranges of several kilometers should be readily achievable. Problems with the large dynamic range still remain. With subnanosecond pulse duration, the dynamic range (limited by the number of photoelectrons which give required signal-to-noise ratios and the number which will cause space charge saturation in the final stages of the photomultiplier) is only 1 or 2 orders of magnitude.

 [redacted]

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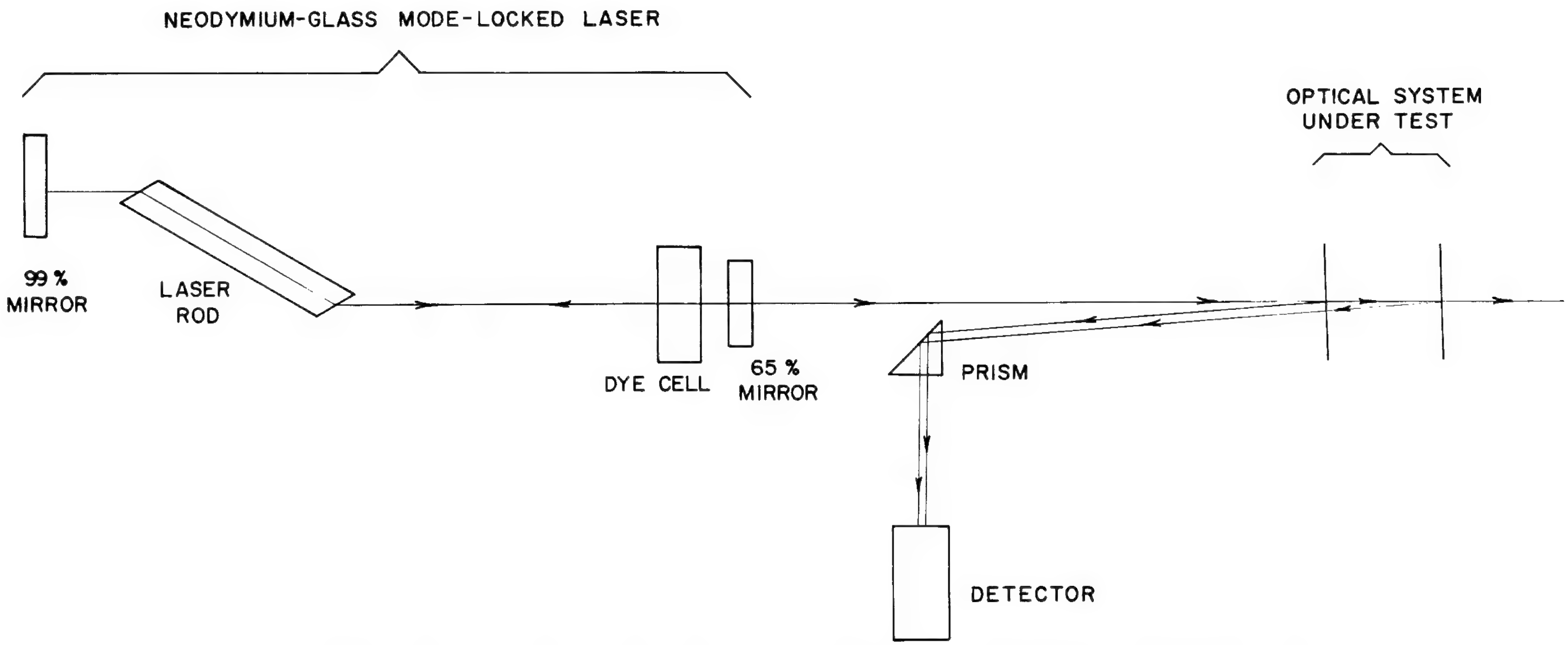
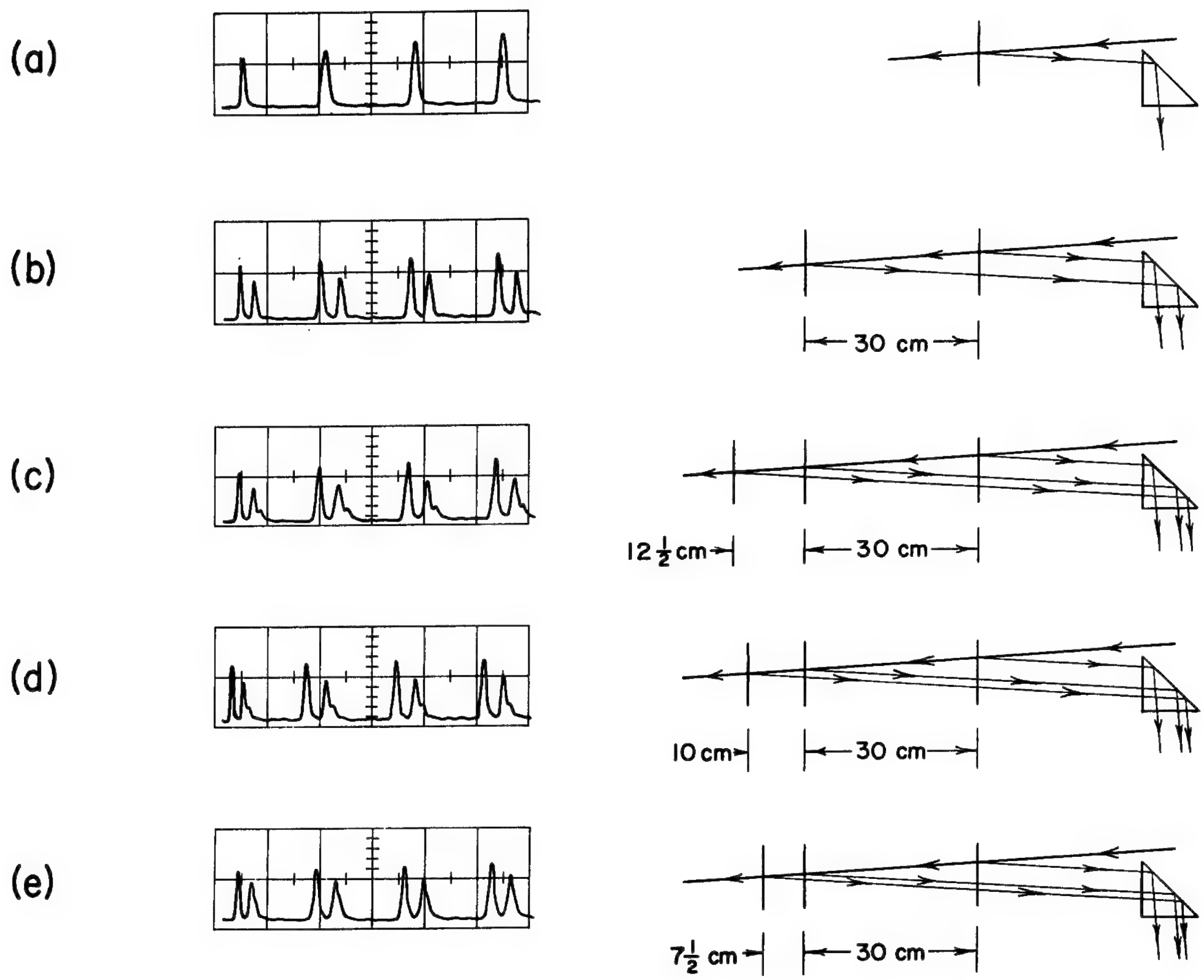


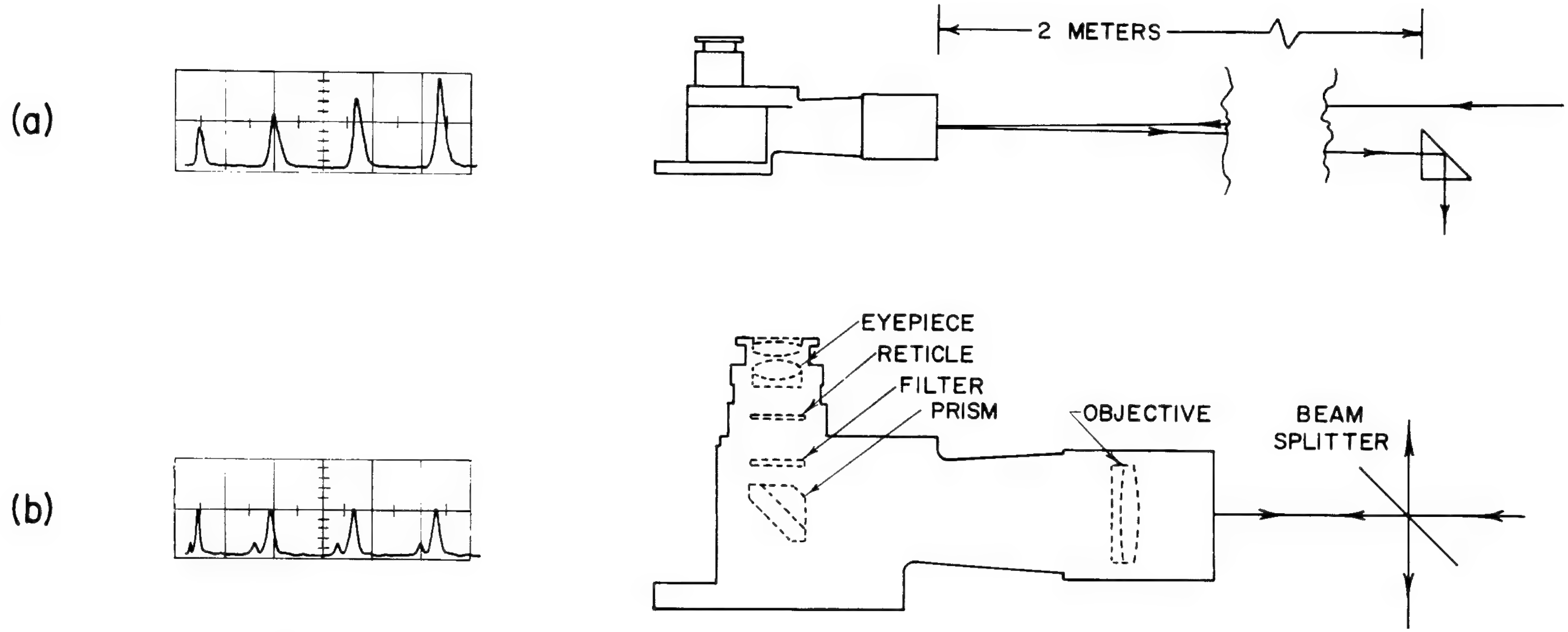
([redacted]) Fig. 1. Typical laboratory setup for observing reflection of ultrashort laser pulses from multiple optical elements.

[redacted]

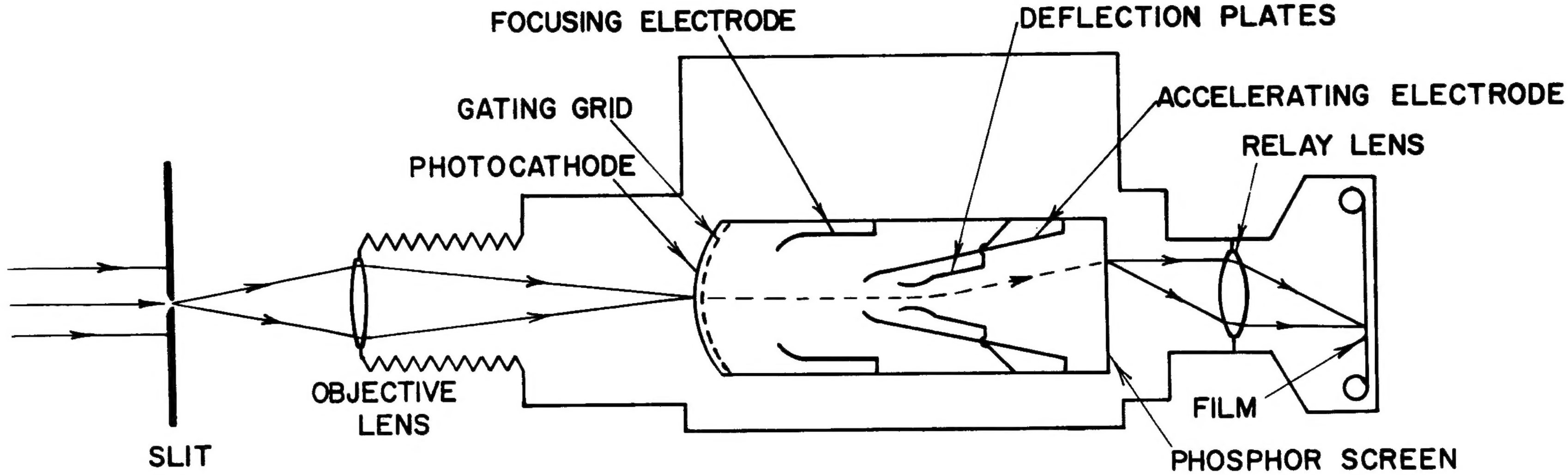


([redacted]) Fig. 2. Multiple reflections of ultrashort laser pulses observed with photodiode and displayed on an oscilloscope. Oscillograms are shown on the left: horizontal time scale is 5 nsec/cm; vertical deflection is intensity in relative units. Corresponding experimental setup is shown on the right.

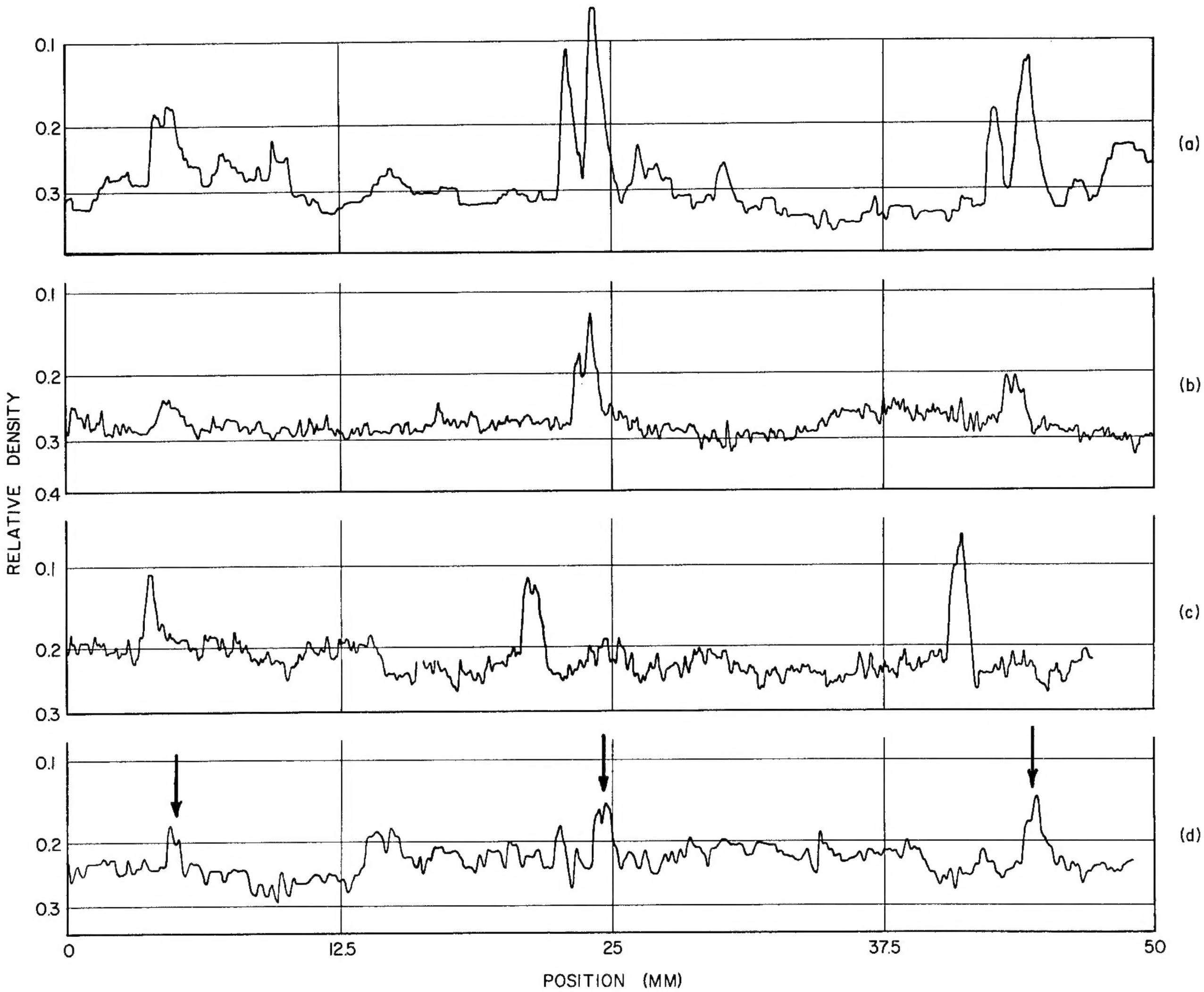
 [redacted]



([redacted]) Fig. 3. Reflected signal from elbow telescope observed with photodiode and oscilloscope. Horizontal time scale is 5 nsec/cm. Experimental setup is shown on the right.



(U) Fig. 4. Diagram of TRW Model 1D1 image converter camera used to time resolve reflected intensities by sweeping the image of a slit illuminated by the reflected signal.



([redacted]) Fig. 5. Densitometer traces of image converter camera streak exposure of slit illuminated by reflected signal. Streak rate of camera was 0.4 nsec/mm. The entrance slit of the camera was illuminated by the reflected radiation of two parallel beam splitters separated by the following distances: (a) 7.5 cm; (b) 3 cm; (c) 2 cm; (d) 1.5 cm. A train of picosecond pulses was employed as the source and reflections associated with three pulses in the train are visible on the figure. The first (left side) is degraded due to gating in the camera.

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13. ABSTRACT

([redacted]) Picosecond optical pulses generated by a neodymium-glass mode-locked laser were employed in laboratory measurements of the retroreflection from optical surfaces. These measurements were directed at a determination of the minimum separation distance between surfaces which could be resolved using either a photodiode or an image converter camera for detection. A minimum resolvable distance of 7.5 cm was obtained with a photodiode, and the camera yielded a value of 1.5 cm. In addition calculations have been made of the range at which the retroreflection technique may be employed for analyzing optical elements using short pulses. Ranges of several kilometers appear feasible.

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